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Force Tracking Impedance Control with Unknown Environment at the Microscale

Bilal Komati, Cédric Clévy and Philippe Lutz

Abstract—A new method to estimate the environment parameters is proposed in order to perform force tracking in impedance control despite the presence of an unknown environment. In impedance force tracking, the location of the environment relative to the robot and the stiffness of the environment should be known. The proposed method estimates the environment location and stiffness using only force and position measurements. The study is done for microscale taking into consideration microscale specificities, especially pull-off force. The impedance control formulation is tested experimentally in a contact transition scenario consisting of a compliant microforce sensor mounted on a microrobotic positioner, and three compliant microstructures with different stiffness. A traditional double mass-spring-damper model of the overall robot is employed to develop the closed-loop impedance control.

I. INTRODUCTION

Force control is important for many microscale applications like biological, medical, microassembly, micromanipulation, etc. It improves the dexterity of the task by providing an additional feedback information. This feedback enables to detect any contact between the microrobot and the environment and guarantees the safety of both the microrobot and the environment by controlling the interaction forces[1]. Furthermore, at the microscale, surface forces are predominant and more influent than volume forces and induce some nonlinear effects, such as adhesion forces. It is notably manifested by pull-off forces, [2], which are naturally present and may affect any surface contact at the microscale. Microrobot control thus differ from macroscale control because microscale control has to overcome such microscale specificities. In addition, the integration of sensors is another limit in microscale which limits the automation and the development of some control algorithms. Although force control is important at the microscale, this topic is not covered like at the macroscale. Some microscale works use quasi-static models for hybrid force/position control [1], [3]. Others use explicit force control [4], [5], impedance control [4], [6] and vision-based force control [7]. In [4], a comparison between explicit force control and impedance control algorithms has been performed for microscale applications. It was proven experimentally that the impedance control presents better performances than explicit force control for microscale applications if the environment parameters are perfectly known which is not usually the case at the microscale. The importance of impedance control is that

it enables dynamic control which improves the control of the microrobot relatively to the use of vision and static approaches at the microscale.

Previous works at the microscale approve that, similar to the macroscale, the impedance control technique proposed by Hogan [8] is a promising approach for controlling the dynamic interaction between a robot and an environment. However, one weak point of the impedance control is the lack of the direct force control capability by specifying a desired force which the explicit force control [9] and hybrid force/position control [10] do. Many researchers have paid attention to this fact and tried to solve the direct force control capability by using adaptive impedance control [11], [12], [13], [14], recursive least square [15], [16]. The recursive least square method used in [15] is difficult to implement and it estimates the environment mass, damping and stiffness within the framework of pure impedance control without tracking a desired force signal because the environment location is not estimated. Most of the developed works use adaptive impedance control to estimate the parameters of the environment. However, the implementation of the parameter estimation in the indirect adaptive controller requires data on the current position and velocity of the end-effector and the interaction force. In practice, especially at the microscale, accurate measurement of absolute velocity at the robot tip is difficult to achieve and induces a challenge in the application of the method. Furthermore, to use the algorithm, the user must specify the gain matrix of the adaptation law which increases the complexity of the method.

In this paper, a new method to estimate the environment location and stiffness is proposed in order to perform force tracking impedance control despite the presence of an unknown environment. This method requires only data on the current position of the end-effector and the interaction force and does not need to specify any gain. The complete control scheme with parameter estimation is easy to implement and guarantees force tracking. Furthermore, a new and easy method to deal with pull-off force is proposed in this paper.

The paper is organized as follows. The system model and impedance control strategy are developed in Section II. The new proposed method for the online estimation of the environment parameters is presented in Section III. Section IV shows the capability of force tracking despite the parameter estimation errors. The experimental setup used in this paper is presented in Section V. Section VI presents the experimental results obtained for the complete impedance control law with parameter estimation integrated into the experimental setup. Section VII concludes the article.

II. SYSTEM MODELING AND CONTROL

In this section, the model of the system used in this paper is discussed. Then, impedance control with force tracking strategy is presented.

A. Model of the Robot and the Environment

A classic robotic scenario is considered in this paper. Consider a robot end effector and let f_e be the current contact force applied by the end effector to the environment once a contact between both is established. For modeling the robot/environment interaction, the environment is presented by a second order mass-spring-damper system like was done in [17]. The system model without contact and with contact is presented in Fig. 1, where m_e , d_e and k_e are respectively the mass, damping and stiffness of the environment, m_m , d_m and k_m are respectively the mass, damping and stiffness of the end effector manipulator, x_s is the position of the positioning stage, x_{sc} is the position of the positioning stage at contact, x is the current position of the robot manipulator and x_e is the position of the environment without any contact. Note that contrary to macrorobotics, most micropositioning devices are position controlled and not force controlled. In this paper, the position of the stage, x_s , is the command of the system and f_e is the force to be controlled.

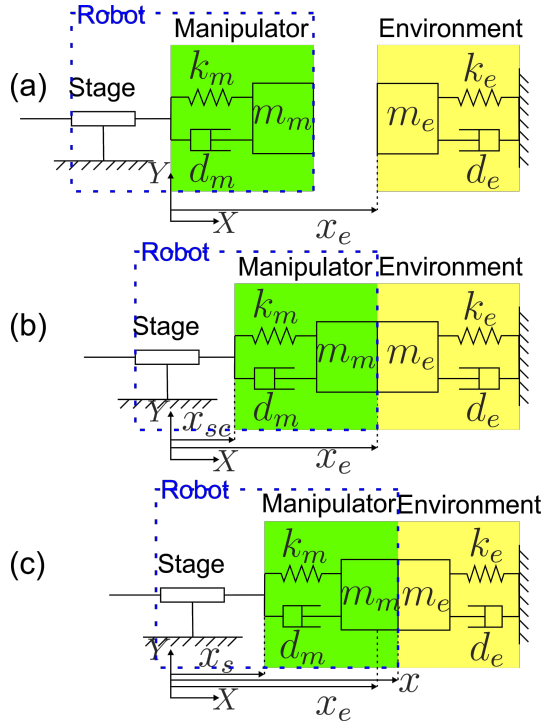


Fig. 1. System model based on mass spring damper: (a) without any contact between the end effector and the environment, (b) just at contact $f_e = 0$ and (c) contact with $f_e \neq 0$.

Using Fig. 1-c, the force applied by the manipulator end effector to the environment is given by (1):

$$f_e = F_{\text{end effector} \rightarrow \text{environment}} = m_e \ddot{x} + d_e \dot{x} + k_e(x - x_e) \quad (1)$$

The force applied by the environment to the manipulator end effector is given by (2):

$$f_m = -f_e = m_m \ddot{x} + d_m(\dot{x} - \dot{x}_s) + k_m(x - x_s) \quad (2)$$

(2) could also be written like in (3)

$$m_m \ddot{x} + d_m \dot{x} + k_m x + f_e = d_m \dot{x}_s + k_m x_s \quad (3)$$

B. Impedance Control with Force Tracking

The objective of impedance control as proposed by Hogan in [8] is to establish a desired user-specified dynamical relationship, referred to as target impedance, between the end-effector position x and the contact force f_e . Typically, the target impedance is chosen as a linear second order system, so that the dynamical relationship between the contact force f_e and the end effector position x can be controlled by a mass-spring-damper system. A common formulation of the target impedance is given by (4) where M_d , D_d and K_d are respectively the desired mass, damping and stiffness of the target impedance, x_r is the reference position, f_r is the reference force and e_f is the force error. The classical impedance control scheme is presented in Bloc I of Figure 2.

$$M_d(\ddot{x} - \ddot{x}_r) + D_d(\dot{x} - \dot{x}_r) + K_d(x - x_r) = f_r - f_e = e_f \quad (4)$$

In any practical implementation of impedance control, a position tracking error, due to the dynamics of the robot, will appear between the end effector position and the desired position calculated by (4). In this case, (4) could be written as in (5) where x_d is desired position trajectory generated.

$$M_d(\ddot{x}_d - \ddot{x}_r) + D_d(\dot{x}_d - \dot{x}_r) + K_d(x_d - x_r) = f_r - f_e \quad (5)$$

Thus, an inner loop Position Control Law (PCL) should be used to let x track x_d . Let $\varepsilon = x_d - x$ represents the position error between the desired position generated by (5) and the current position of environment. Using the result of [11], the steady state force error is given by:

$$e_f^{ss} = k_{eq} \left[\frac{f_r}{k_e} + x_e + \varepsilon - x_r \right] \quad (6)$$

where $k_{eq} = \frac{K_d k_e}{K_d + k_e}$ is the equivalent stiffness of the target impedance and the environment. Equation (6) shows that if an inner loop position control law is used in such a way to have a zero steady state position error ($\varepsilon \rightarrow 0$) and the reference position is chosen precisely as in (7), then the steady state force error will be cancelled ($e_f^{ss} \rightarrow 0$).

$$x_r = x_e + \frac{f_r}{k_e} \quad (7)$$

Equation (7) shows that if the precise location of the environment x_e and the exact value of the environment stiffness k_e are known then a reference position trajectory x_r could be generated according to (7) to exert the desired contact force f_r on the environment. However, in practice the values x_e and k_e are not known perfectly and, as a result, the desired force

f_r will not be exerted on the environment. Let $(\Delta x_e, \Delta k_e)$ be the uncertainties on the location of the environment, that is:

$$\begin{aligned} x_e &= \hat{x}_e + \Delta x_e \\ k_e &= \hat{k}_e + \Delta k_e \end{aligned} \quad (8)$$

where \hat{x}_e and \hat{k}_e are respectively the estimated values of x_e and k_e . Then using the reference position $x_r = \hat{x}_e + \frac{f_r}{\hat{k}_e}$ given in (7), the steady state force error given in (6) could be written as in (9) which shows that if the $(\Delta x_e, \Delta k_e)$ are big then the steady state force error is also big.

$$e_f^{ss} = \frac{K_d}{K_d + \hat{k}_e + \Delta k_e} \left[\hat{k}_e \Delta x_e - \frac{\Delta k_e}{\hat{k}_e} f_r + (\Delta x_e)(\Delta k_e) \right] \quad (9)$$

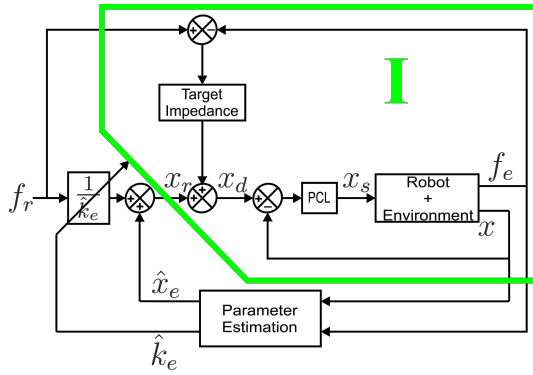


Fig. 2. Position based impedance control system with force tracking where PCL is an inner loop Position Control Loop. Bloc I is the classical position based impedance control scheme without force tracking.

III. ENVIRONMENTAL LOCATION AND STIFFNESS ESTIMATION TECHNIQUE

As shown in the previous section, in order to achieve a force tracking in the impedance control scheme, the environment location x_e and the environment stiffness k_e should be known or estimated. Many techniques have been used in the past including adaptive control and recursive least square. These methods are usually difficult to be implemented to the system and require data on the current position and velocity of the end effector and the interaction forces which is difficult at the microscale due to the lack of velocity sensors. In this section, a new simple on line estimation method is proposed in order to estimate the environment location x_e and its stiffness k_e . The proposed method is easy to be implemented, it does not need to specify adaptive gains and it requires only data on the location of the end-effector and the interaction forces.

The first step is to determine the location of the environment x_e . The idea is to apply the impedance control law presented in the previous section using assumptions \hat{x}_e^0 and \hat{k}_e^0 of x_e and k_e . Once the control law is applied, a transition between non contact and contact happens as shown in Fig. 1-a and 1-c. During this transition, an on line acquisition of the force and position measurements is achieved and when a contact is detected the location of the environment, \hat{x}_e , is determined by the past value of the position measurement.

Due to the noisy force signal measurement (amplitude of noise $\pm 5\mu\text{N}$ in our case), a dead zone is defined ($5\mu\text{N}$) and a contact is taken into consideration if the force measurement is bigger than the dead zone.

Once the environment location is estimated, the environment stiffness is estimated using the static part of (1):

$$\hat{k}_e = \frac{f_e}{x - \hat{x}_e} \quad \text{if } x > \hat{x}_e \quad (10)$$

Note that ignoring the dynamical part of (1) could modify the desired dynamic of the system but it will not affect the steady state part. Using (6), we can write:

$$x_r = \hat{x}_e + \frac{f_r}{\hat{k}_e} = \hat{x}_e + \frac{f_r}{f_e} (x - \hat{x}_e) \Leftrightarrow x_r - \hat{x}_e = \frac{f_r}{f_e} (x - \hat{x}_e) \quad (11)$$

Using (11) if x tracks x_r , then f_e will track f_r .

The complete impedance control scheme with parameter estimation used in this paper is given in Fig. 2.

IV. FORCE TRACKING DESPITE ESTIMATION ERRORS

Using (1) and (10), the steady state force applied on the environment, f_e^{ss} , could be written in the two forms of (12):

$$f_e^{ss} = \hat{k}_e (x^{ss} - \hat{x}_e) = k_e (x^{ss} - x_e) \quad (12)$$

where x^{ss} is the position of the environment in steady state. Replacing (8) in (12), the following could be deduced:

$$\hat{k}_e x^{ss} - \hat{k}_e \hat{x}_e = (\hat{k}_e + \Delta k_e) (x^{ss} - \hat{x}_e - \Delta x_e) \quad (13)$$

After developing (13), (14) can be derived:

$$\Delta k_e = \frac{\hat{k}_e \Delta x_e}{x^{ss} - \hat{x}_e - \Delta x_e} \quad (14)$$

Using (12), $x^{ss} - \hat{x}_e = \frac{f_e^{ss}}{\hat{k}_e}$, and replacing the latter in (14), (15) can be derived:

$$\Delta k_e = \frac{\hat{k}_e^2 \Delta x_e}{f_e^{ss} - \hat{k}_e \Delta x_e} \quad (15)$$

Thus, the error in the estimation of the stiffness of the environment, Δk_e , increases if the error of the estimation of the position, Δx_e , increases as (15) shows. If the estimation of the position of the environment is small then the estimation of the stiffness is small.

Replacing (15) in (9), (16) can be derived:

$$e_f^{ss} = \frac{-K_d \hat{k}_e \Delta x_e}{K_d f_e^{ss} + \hat{k}_e f_e^{ss} - K_d \hat{k}_e \Delta x_e} e_f^{ss} \quad (16)$$

Equation (16) is true if and only if:

$$\begin{cases} e_f^{ss} = 0 \\ \text{or:} \\ \frac{-K_d \hat{k}_e \Delta x_e}{K_d f_e^{ss} + \hat{k}_e f_e^{ss} - K_d \hat{k}_e \Delta x_e} = 1 \end{cases} \quad (17)$$

Equation (17) is equivalent to:

$$\begin{cases} e_f^{ss} = 0 \\ \text{or:} \\ f_e^{ss} = 0 \end{cases} \quad (18)$$

Equation (18) shows that using the parameter estimation technique presented in section III, once a contact force is detected ($f_e \neq 0$), the steady state force error is always zero and the force tracking is guaranteed even if big estimation errors exist on x_e and k_e because the errors are compensated.

V. EXPERIMENTAL SETUP

The hardware shown in Fig. 3 was used to control the interaction between a MEMS force sensor and a compliant environment. A microstructure made of 300 μ m of thickness of glass was used as the passive compliant mechanism of the environment and it was attached to a stationary base. A Femto-Tools force sensing probe FT-S270, with a sensing range of 2mN and a resolution of 0.4 μ N, used as an end effector, was attached to a positioning stage. The force sensor comprises a probe of 3mm of length and 50 μ m of thickness, that moves along X direction (according to Fig. 3) once a force is applied at its tip. The displacement is converted into a voltage thanks to a capacitive variation measured by a dedicated circuit. The maximal contact surface between the force sensor and the environment is 50 μ m \times 50 μ m. The positioning stage is a PXY D12 - piezo XY scan positioner from PiezoSystemJena with a travel range of 200 μ m. It has an internal capacitive sensor to measure the displacement of the stage along its two axis. The positioning stage was controlled and the force and the position feedback were acquired through a dSPACE1104 board.

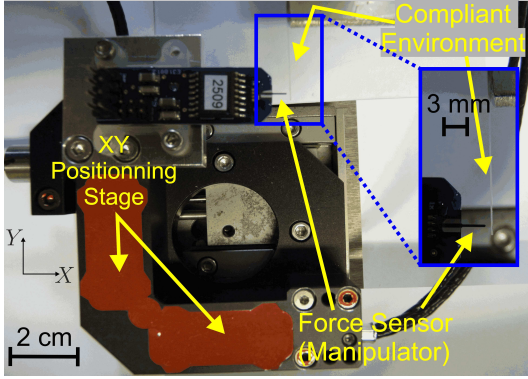


Fig. 3. Experimental setup.

VI. EXPERIMENTAL RESULTS

In this section, the impedance control with force tracking scheme presented in Section II is implemented via a dSPACE 1104 board, with a sampling frequency 10kHz without any knowledge of the location and the stiffness of the environment. The method presented in Section III is used to estimate x_e and k_e . First, the maximal errors on the estimation of the environment parameters (x_e and k_e) are evaluated using the experimental setup presented in section V. Then, several object stiffness are used to test the effectiveness of the impedance control with force tracking scheme presented in Section II.

A. Maximal error on the estimation of x_e

The maximal speed of the positioning stage is 1mm/s. The sampling time used in this paper is 100 μ s. Indeed, the maximal displacement of the positioning stage in 100 μ s is 100nm. Using these results, the maximal error on the estimation of the environment location is 100nm.

B. Maximal error on the estimation of k_e

The error on the estimation of the stiffness could be deduced from (15) which can be written as:

$$\frac{\Delta k_e}{\hat{k}_e} = \frac{\hat{k}_e \Delta x_e}{f_e^{ss} - \hat{k}_e \Delta x_e} \quad (19)$$

Inducing the maximal error on the estimation of the location (0.1 μ m) in (19), the following can be deduced:

$$\hat{k}_e \Delta x_e < 0.1 \hat{k}_e \quad (20)$$

Using (19) and (20), the following is deduced:

$$\frac{\Delta k_e}{\hat{k}_e} < \frac{0.1 \hat{k}_e}{f_e^{ss} - 0.1 \hat{k}_e} \quad (21)$$

Equation (21) shows that the relative error on the estimation of the stiffness increases if the stiffness is big and the steady state force is small. Considering $f_e^{ss} = 1000\mu$ N and the stiffness of the environment is 1000N/m, which is a big stiffness for the microcomponents, then, using (21) the maximal error on the estimation of the stiffness could reach 11%. The calculated errors on the location and the stiffness of the environment are considered in the worst case and in experiments they are much smaller. However, as already said, the parameter estimation errors are compensated to have finally a zero steady state force error as shown in section IV.

C. Experimental investigations

To test the impedance control with force tracking scheme presented in Section II, several object stiffness are used. Initial values \hat{x}_e^0 and \hat{k}_e^0 are used as assumptions for x_e and k_e . Two scenarios exist in function of the presumption of the location of the environment \hat{x}_e^0 :

- if $x_r = \hat{x}_e^0 + \frac{f_r}{\hat{k}_e^0} < x_e$: in this case, no contact appears and the parameters could be estimated and accordingly the force reference could not be tracked like it was shown in the second equation of (18) ($f_e^{ss} = 0$),
- if $x_r = \hat{x}_e^0 + \frac{f_r}{\hat{k}_e^0} > x_e$: in this case, a contact appears and the parameters are estimated and the force reference is tracked like it was shown in the first equation of (18) ($e_f^{ss} = 0$).

Taking into consideration the two scenarios, the assumption of the environment location \hat{x}_e^0 is chosen big enough in order to guarantee that a contact happens without any force reference. The location is then estimated to be \hat{x}_e and the end effector's position x tracks \hat{x}_e . Once a reference force f_r is applied, the controller manages to let f_e tracks f_r .

Figure 4 shows the impedance control scheme with force tracking in presence of an environment with a stiffness of 72.5N/m. The initial position of the environment is 12.5

μm . At the beginning of the experiment, the controller is turned off, the assumptions of the position and the stiffness of the environment are respectively $30\mu\text{m}$ and 100N/m . At $t = 0.04\text{s}$; the controller is turned *ON* and the stage moves to let x_r tracks \hat{x}_e^0 because the force reference f_r and the measured force f_e are null. As $\hat{x}_e^0 > x_e$, a contact appears at $t = 0.05\text{s}$. Because a force is detected, \hat{x}_e is estimated and it is equal to $12.51\mu\text{m}$. The estimation of the environment location is fixed in the rest of the experiment. A reference force is set to 1mN at $t = 0.2\text{s}$. The estimation of the stiffness along (10) starts and the controller is able to track the force reference with a response time of 150ms and an overshoot of 20% . The stiffness of the environment is estimated to be around 71.95N/m . The estimation of the stiffness will then be used in the rest of the experiment. To test the capability of the controller and the effectiveness of the parameter estimation technique, another force reference of 1.5mN is applied at $t = 0.666\text{ms}$. The controller is able to cancel the steady state force error in 70ms with no overshoot. The controller is tested in the other direction i.e. if the force reference decreases. The controller performances are almost the same if the force reference goes from 1.5mN to 1mN and from 1mN to zero. The error on the estimation of the environment is $\Delta x_e = 0.01\mu\text{m}$ and on the environment stiffness is $\Delta k_e = 0.55\text{N/m}$. However, despite the error on the parameter estimation, f_e tracks f_r . At $t = 1.885\text{s}$, f_e returns to zero but the contact is not broken due to the pull-off force which has sticking effects and prevent the breaking of the contact. A simple method is proposed to break the contact by cancelling the effect of the pull-off force by applying a negative force reference as shown in Figure 5.

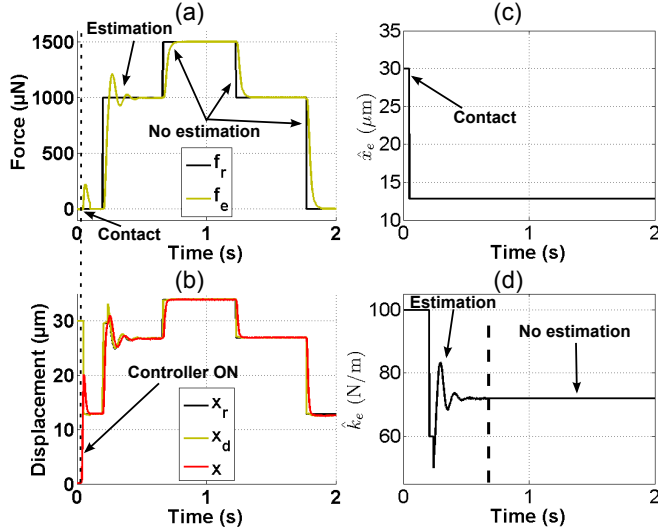


Fig. 4. Impedance control with force tracking in presence of an environment of stiffness 72.6N/m (a) contact force f_e is compared relative to the force reference f_r (b) position of the environment is compared to the reference x_r and the desired x_d positions (c) Environment location \hat{x}_e (d) Environment stiffness \hat{k}_e .

Figure 5 shows the same procedure used in Figure 4 in presence of an environment with stiffness 976N/m which is a relative stiff environment in microscale applications. The en-

vironment location is first estimated with an error of $0.05\mu\text{m}$. Once a force reference is applied, some oscillations appear in the response of the system. Despite the big overshoot present in the system, the stiffness of the environment is estimated 930N/m with a small error (5%) and the force f_e tracks the reference force f_r with a response time of 386ms and an overshoot of 65% .

As already discussed, in order to break the contact, a negative force reference is applied at $t = 1.321\text{s}$ and a pull-off force of $116\mu\text{N}$ appears at $t = 1.342\text{s}$ as shown in Figure 5. Then, the contact is broken and the force f_e returns to zero. Hence, another advantage of the proposed control method is that it can deal with pull-off force by simply applying negative force reference.

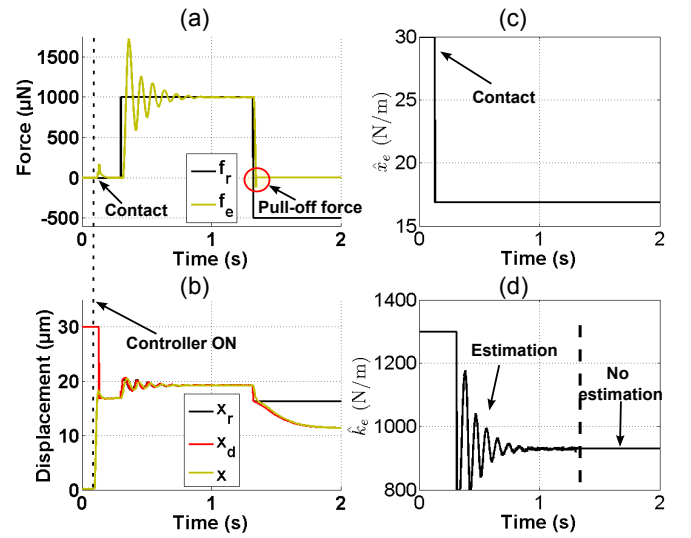


Fig. 5. Impedance control with force tracking in presence of an environment of stiffness 976N/m (a) contact force f_e is compared relative to the force reference f_r (b) position of the environment is compared to the reference x_r and the desired x_d positions (c) Environment location \hat{x}_e (d) Environment stiffness \hat{k}_e . A pull-off force appears at $t = 1.342\text{s}$

In Table I, a comparison between the behavior of the proposed control scheme in presence of three environments with three different stiffness is done. The steady state force error is null in the three cases despite the parameter estimation errors. The overshoot of the system and the response time increase if the stiffness of the environment increases. The estimation of the parameters is precise with a relative small error in the three cases which is not only important but so difficult in microscale applications. The force tracking impedance control scheme with the proposed estimation method presents better performances comparing it to other methods of parameter estimation where bigger force error exists like in [6]. Indeed, the response time is faster than in [12], [13], [16] and the overshoot is smaller than in [11], [13], [16]. The maximal estimation error of the environment stiffness using the proposed method is 11% where it is 12.5% using the indirect adaptive control [16].

Stiffness(N/m)	72.5	469	976
e_p^{ss}	0	0	0
$\Delta x_e(\mu\text{m})$	0.1	0.087	0.05
$\Delta k_e(\%)$	0.7	3.2	5
Response time (ms)	150	192	386
Overshoot (%)	20	25	65

TABLE I

EXPERIMENTAL RESULTS COMPARISON FOR THREE ENVIRONMENTS
WITH THREE DIFFERENT STIFFNESSES.

VII. CONCLUSION

In this paper, a new method to estimate the environment parameters is proposed in order to perform force tracking in impedance control despite the presence of an unknown environment. The proposed method estimates the environment location and stiffness using only force and position measurements. The study is done for microscale taking into consideration microscale specificities, especially pull-off force.

In impedance force tracking, the location of the environment relative to the robot and the stiffness of the environment should be known which is difficult, especially at the microscale. The proposed estimation method is able to estimate the environment location with an error less than $0.1\mu\text{m}$ and the environment stiffness less than 11%. These values are considered in the worst cases while in experiments the environment stiffness error was smaller than 5%. However, the control scheme is able to cancel the steady state force error despite the estimation errors on the environment parameters. The complete impedance control scheme is able to track the force reference with a response time of 150ms and an overshoot of 20% in presence of flexible environments ($k_e < 100\text{N/m}$) while the response time reaches 386ms and the overshoot reaches 65% in presence of stiff environment (around 1000N/m). Furthermore, a simple method to deal with pull-off force is proposed by applying a negative force reference to the system.

Three main advantages exist for using the proposed estimation method relative to other existing methods. The first advantage is that it requires data only on the current location of the end-effector and the interaction force which is an advantage comparing to the indirect adaptive impedance control where an additional data on the velocity of the end-effector is required. This point is important, especially at the microscale, because accurate measurement of absolute velocity at the robot tip is difficult to achieve and most of the microscale sensors measures only the position of the end-effector which induces a challenge in the application of the method. The second advantage is that no adaptive gains need to be specified in order to perform parameter estimation which simplifies the use of the estimation method. The third advantage is that this method is easy to be implemented and presents better performances than existing work on adaptive impedance control. Hence, the complete force tracking impedance control scheme with the proposed parameter estimation method is suitable for microscale applications

where the stiffness and the location of the environment are unknown and variable.

This paper shows that the use of impedance control with force tracking for microscale applications is a promising topic for force control of some microrobotics, robotic microassembly and micromanipulation applications. This work was done for a 1 DOF moving stage case study and can be performed for more complex systems.

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